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(71) Applicant: **HOXAN CORPORATION**
2, 1-chome, Nishi Kita-Sanjyo
Chuo-ku Sapporo-shi Hokkaido(JP)

(72) Inventor: **Matsumoto Kazutake**
Teion Gijutu Kaihatsu Sentaa Hoxan Corp.
16-2
Ninomiya 3-chome Tsukuba-shi
Ibaraki-ken(jp)

Inventor: **Wakusawa Atsushi**
Teion Gijutu Kaihatsu Sentaa Hoxan Corp.
16-2
Ninomiya 3-chome Tsukuba-shi
Ibaraki-ken(jp)

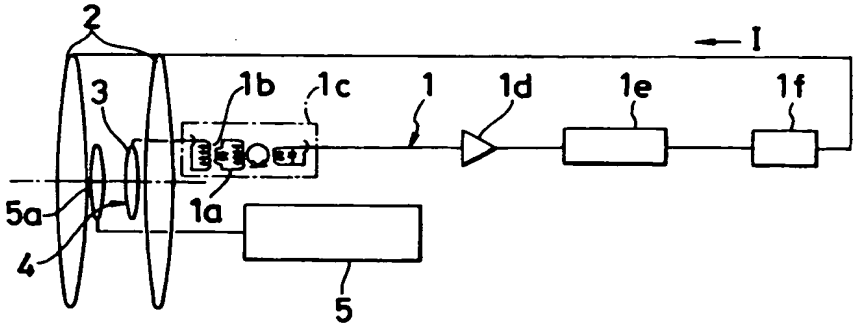
Inventor: **Fujioka Koji**
Teion Gijutu Kaihatsu Sentaa Hoxan Corp.
16-2
Ninomiya 3-chome Tsukuba-shi
Ibaraki-ken(jp)

(74) Representative: **Gibson, Stewart Harry**
URQUHART-DYKES & LORD Business
Technology Centre Senghennydd Road
Cardiff CF2 4AY South Wales(GB)

(54) Magnetic noise reducing device for a squid magnetometer.

(57) A magnetic noise reducing device can effectively produce a practically noiseless space that can reduce environmental magnetic noise harmful for measuring biomagnetism with a high magnetism damping factor in low frequency range. The magnetic noise reducing device comprises a Superconducting Quantum Interference Devices (SQUID) flux meter 1 and a pair of noise cancelling coils 2 as minimum components, the feedback current I produced by the SQUID flux meter 1 being supplied to the noise cancelling coils 2, the magnetic flux detecting coil of the SQUID flux meter being arranged within a specific central space 4 defined by the noise cancelling coils 2 for effective reduction of magnetic noise within that space.

FIG.1(A)



EP 0 514 027 A2

This invention relates to a magnetic noise reducing device for a Superconducting Quantum Interference Device (SQUID) magnetometer or flux meter.

The Superconducting Quantum Interference Device (SQUID) comprises a ring of superconducting material. When the SQUID is cooled through its transition temperature in the presence of a magnetic field, and then the field is removed, a magnetic flux is trapped within the ring. This trapped flux is maintained by a supercurrent flowing in the device. A supercurrent is a current which flows around the ring in the absence of an applied voltage, and superconducting materials are able to sustain such currents up to a critical value. the value of this critical current will oscillate under an applied magnetic field due to phase changes across junctions in the superconducting material. Small changed in applied field strength create a measurable exchange in the critical current.

It will be appreciated that a SQUID can be used as a highly sensitivity magnetometer in an apparatus for measuring biomagnetism in living bodies. However, when measuring such low level magnetic fields it is important to shield the SQUID from external environmental noise.

As illustrated in Fig. 2(A) of the accompanying drawings, the environmental magnetic noise is correlated with 1/f (f = frequency) in the low frequency range, showing a level between $1x10^{-10}$ and $1x10^{-9}T(Hz)^{-1/2}$ for the frequency of 1Hz and a higher level for low frequencies. On the other hand, the level of the biomagnetism of a living body to be detected is found between 10^{-14} and 10^{-9} - (depending on the intensity, the depth, the direction of emission of the signal generating source).

The frequency bandwidth (B) involved in the measurement of biomagnetism is normally around DC to 1kHz. Since the noise level in a setting for measuring the biomagnetism of a living body is expressed by $Bnx\ B^{1/2}$ (where Bn is magnetic noise per unit frequency), it will be approximately thirty two (32) times as large as that of $1x10^{-9}T(Hz)^{-1/2}$ for DC to 1kHz. Besides, the frequency characteristics of the noise involved need to be taken into consideration. If the noise level is of a magnitude of $5x10^{-9}T$ and a magnetic attenuation in the order of 10^{-14} is involved, the S/N ratio will be 1 for a signal of 10^{-14}.

In view of the above facts, a magnetic noise reducing device is required to have a magnetism damping factor of 10^5 to 10^6 and be specifically effective for low frequency noises (less than 1Hz) if it is effectively used for measuring biomagnetism.

Known means for reducing magnetic noise and means for canceling environmental magnetic noise include the followings.

a) magnetic shield room

This is a room constructed by using magnetically highly permeable materials such as Permalloy and providing magnetic noise damping areas inside the room.

Fig. 5 is a graph showing the frequency dependency of the magnetism damping factor of such a magnetic shield room. In Fig. 5, curves L_1 and L_2 show the magnetic damping factors of two magnetic shield rooms prepared by using walls having a multi-layered structure of aluminum and Permalloy plates. The magnetic damping factor of such a room is increased as the number of aluminum and Permalloy layers grows.

As is obvious from Fig. 5, such a magnetic shield room does not show a large magnetism damping factor for low frequency magnetic noise. Moreover, such a room inevitably provide only a narrow closed space for measurement and entails a high building cost of several hundred million yen.

b) electric method for canceling magnetic noise

This is a method using a device as illustrated in Fig. 6 to eliminate the noise component of output signal by determining the difference between the measurement of a signal detecting SQUID flux meter SC1 and that of a reference SQUID flux meter SC2. In Fig. 6, arrow M denotes signal, arrow N denotes noise, P1 and P2 denote controllers, Q and R respectively denote a signal processing circuit and the output terminal of the circuit.

Since such a device does not and cannot remove the magnetic field existing in the signal detecting space, corrective means may be additionally required for each of the channels involved if a multi-channel SQUID system is used.

c) gradiometer

As is known, a SQUID flux meter normally comprises a magnetic flux transformer constituted by a magnetic flux detecting coil MC, an input coil IP and a SQUID inductance SI as illustrated in Fig. 7. If the spatial gradient is known for the magnetic field to be detected, the gradiometer to be used for magnetic noise reduction are so designed that any magnetic fields having a gradient lower than it may be canceled.

If a magnet meter U, a primary differential gradiometer U1 and a secondary differential gradiometer U2 are arranged as illustrated in Fig. 8 to form a gradiometer for the purpose of magnetic noise reduction, such a gradiometer can selectively cancel even magnetic fields (primary differential) and/or magnetic fields up to the primary gradient (secondary differential) on site or produce $\delta Bz/\delta x$, $\delta Bz/\delta y$ and/or $\delta Bx/\delta z$ according to the purpose of measurement.

A gradiometer as described above is, how-

ever, accompanied by the disadvantage of a low sensitivity of a SQUID flux meter for magnetic flux density of higher orders, the sensitivity being remarkably lowered in terms of distance (in the Z direction for $\delta Bz/\delta z$) so that the canceling efficiency is determined by the winding balance, making the rate of noise reduction normally as poor as 10^2 to 10^4.

Contrary to the above described disadvantages of known magnetic noise reducing devices, a magnetic noise reducing device according to the invention is based on the principle of nil magnetic field detection that has been used for SQUID flux meters comprising a SQUID circuit having a feedback loop for making a SQUID element always show a nil magnetic field intensity. In other words, in a magnetic noise reducing device according to the invention, the feedback current of each SQUID flux meter it comprises is supplied not to a SQUID element but to corresponding noise canceling coils, the magnetic flux detecting coil of the SQUID flux meter being arranged within a given space defined by the surrounding noise canceling coils in order to operate the said magnetic flux detecting coil as a zero-level detecting coil so that said space defined by the noise canceling coils provides a space that can be effectively shut out magnetic noise.

More specifically, according to the present invention, there is provided a magnetic noise reducing device comprising an appropriate number of noise canceling coils and corresponding matching SQUID flux meters each having a magnetic flux detecting coil arranged within a specific space defined by the corresponding noise canceling coils, the output of each of said SQUID flux meter being supplied to said corresponding noise canceling coils as a feedback current.

Thus, with a magnetic noise reducing device according to the invention, a feedback current is supplied to a number of noise canceling coils not from an ordinary feedback circuit but from the corresponding SQUID flux meter.

Since the magnetic flux detecting coil of each of the SQUID flux meters is arranged within a magnetic space defined by the corresponding noise canceling coils, it operates as a nil detector. Thus, the noise canceling coils can provide a zero-magnetism space within a given space regarding the environmental magnetic noise.

Now, the present invention will be described in greater detail by referring to the accompanying drawings that illustrate preferred embodiments of the invention.

Figs. 1(A) and 1(B) are circuit diagrams of two different embodiments of the invention.

Figs. 2(A) and 2(B) are schematically illustrated spectra of the magnetic noise measured at the central space of a device according to the invention respectively when the device is not operating and when it is operating.

Fig. 3 is a pen-corder graph showing changes with time in the magnetic noise measured at the central space of a device according to the invention when it is not operating.

Fig. 4 is a pen-corder graph similar to that of Fig. 3 but recorded when the device is operating.

Fig. 5 is a graph showing the relationship between the magnetism damping factor and the frequency of a known magnetic shield room.

Fig. 6 is a circuit diagram of a known apparatus for electrically canceling magnetic noise.

Fig. 7 is a schematic illustration showing the principal components of a known SQUID flux meter.

Fig. 8 is a schematic illustration showing the principal components of a known gradiometer.

Firstly, some aspects of the spatial properties of environmental magnetic noise will be described. The intensity of magnetic field produced by the source of magnetic noise is expressed in terms of distance by a differential polynomial of 0th to nth order. When, however, the distance between the noise source and the space of measurement is very large, the intensity of magnetic field can be regarded as substantially even (0th) within the space.

While sources of magnetic noise are normally located very far from the space of measurement, they are not identifiable. Therefore, the intensity of magnetic field in the space of measurement can be expressed only by using a differential polynomial of an order higher than 0th. Thus, a magnetic noise reducing device according to the invention utilizes a combination of a SQUID flux meter designed to detect a magnetic field involving an appropriate order (e.g., one as shown in Fig. 8) and a number of noise canceling coils that produce a magnetic space of a corresponding order in order to accommodate existing noise spaces.

For instance, a magnet meter (0th) as illustrated in Fig. 8 to be used for the magnetic flux detecting coil of the SQUID flux meter and Helmholtz coils to be used for the noise canceling coils may provide a suitable combination for removing the 0th order component of the magnetic field. A different combination may likewise provide a magnetic noise reducing device appropriate for removing magnetic noise of higher orders.

Now, a preferred first embodiment of the magnetic noise reducing device of the invention comprising a SQUID flux meter 1 and a pair of noise canceling coils 2 that are Helmholtz coils will be described by referring to Fig. 1(A). Reference numeral 3 in Fig. 1(A) denotes a magnetic flux detecting coil of the SQUID flux meter 1 arranged within a given central space 4 formed between the pair of

Helmholtz coils which are located in parallel with each other with a given distance separating them in such a manner that said magnetic flux detecting coil 3 is coaxial with the Helmholtz coils.

While the noise canceling coils 2 produces an even magnetic field showing no magnetic gradient, such a magnetic field is possible to exist only within a given limited central space. A larger even magnetic field can be produced only by using larger coils for the noise canceling coils 2. For application of this embodiment, it is assumed that the noise to be eliminated is generated by noise sources located considerably far away from the embodiment and arranged along the axis of the coils. Such a device, therefore, may be called a uniaxial device.

Referring to Fig. 1(A), 1b denotes a magnetic flux transformer inserted between the magnetic flux detecting coil and an input coil 1a of a known type and 1c denotes a SQUID element of a type normally used for a SQUID flux meter 1. A preamplifier 1d, a SQUID controller 1e and a voltage-current converter 1f are serially arranged in the above order to the output side of the SQUID element 1c so that the output of the voltage-current converter 1f, or a feedback current I, is supplied to the Helmholtz coils that constitute noise canceling coils 2 and are arranged in a coaxial relationship with the magnetic flux detecting coil 3.

While the embodiment of Fig. 1(A) is only effective for eliminating magnetic noise of 0th gradient along a single common axis of a pair of Helmholtz coils, the embodiment of Fig. 1(B) comprises three pairs of Helmholtz coils 2x, 2y, 2z arranged along respective axes x, y, z and corresponding SQUID flux meters 1x, 1y, 1z for the respective Helmholtz coils 2x, 2y, 2z so that feedback currents Ix, Iy, Iz of the respective SQUID flux meters are supplied to the Helmholts coils 2x, 2y, 2z respectively, the magnetic flux detecting coils 3x, 3y, 3z of the respective SQUID flux meters 1x, 1y, 1z being arranged in a given central space 4 defined by the Helmholts coils 2x, 2y, 2z.

With such an arrangement, the embodiment can produce a magnetically shielded three dimensional space generated by the three magnetic flux detecting coils 3x, 3y, 3z and three Helmholtz coils 2x, 2y, 2z.

In the above described embodiment for producing a magnetically shielded three dimensional space, the magnetic flux detecting coils 3x, 3y, 3z may have any angular relationship with the respective Helmholtz coils 2x, 2y, 2z (provided that the axes of the coils 3x 2x rectangularly cross with each other). Therefore, the magnetic flux detecting coils 3x, 3y, 3z may take any appropriate positions.

This fact means that the magnetic flux detecting coils for measuring the biomagnetism of a subject (that correspond to the coil 5a of Fig. 1(A) as described below) provides an advantage that they may take any form and angle.

In an experiment conducted by using the embodiment of Fig. 1(A), the magnetic flux detecting coil of the SQUID flux meter 1 was a magnet meter having five turns and a diameter of 24mm and each of the Helmholtz coils had 72 turns and a diameter of 1,590mm in order to accommodate feedback current I up to ±7mA. The magnitude of the effective magnetic field for noise cancellation was 560nT.

Reference numeral 5 in Fig. 1(A) denotes another SQUID flux meter which is identical with the SQUID flux meter 1 (although its feedback current is returned to its SQUID element), which is also provided to measure the environmental magnetic field noise within the given central space 4 as well as the magnetic field noise that appears when the embodiment is operated to activate the active shield system of the embodiment so that the magnetic damping factor may be determined from the ratio of the two noises. Reference numeral 5a in Fig. 1(A) denotes the magnetic flux detecting coil of the SQUID flux meter 5 which is coaxially separated from the magnetic flux detecting coil 3 of the SQUID flux meter 1 by 100mm.

Figs. 2(A) and 2(B) schematically show the results of measurement in the above described experiment using the SQUID flux meter 5 of the embodiment of Fig. 1(A). The measured frequency range was from 10mHz to 10kHz. In Figs. 2(A) and 2(B), there are shown the magnetic noise spectra of the embodiment of Fig. 1(A) obtained in the above experiment respectively when the active magnetic shield was not activated and when it was activated.

As is apparent from the above results of measurement, the shielding effect of the embodiment is conspicuous below 100Hz, the magnetism damping factors for 0.5Hz, 1Hz, 10Hz, 50Hz and 100Hz being respectively 900, 700, 120, 25 and 14.

Figs. 3 and 4 show the results of measurement using a pen-corder, the former being a record chart obtained when the active shield system was not activated, the latter being a chart obtained when the system was activated.

The magnetic noise levels having a magnitude of several to tens of nT as shown in Fig. 3 represent a noise generated when an automobile passed on a nearby road. Fig. 4 shows that the peak level of such a noise can be reduced to less than 100pT, proving that the embodiment has an active shield factor greater than 100.

It was found later that the magnetic flux detecting coil 3 and the Helmholtz coils had been displaced from their respective proper positions during the measurement. From this fact, the embodi-

ment can be expected to show a magnetism damping factor much greater than 100 with respect to the average magnetic field in low frequency range for an even magnetic field if the circuit constants, the positional displacement of the coils and the sameness of the Helmholtz coils are improved.

It was also found that the use of a magnetic noise reducing device according to the invention and a conventional magnetic shield room having a simple construction as describe earlier in combination provides a remarkable noise reducing effect which is particularly useful for the measurement of biomagnetism.

As is apparent from the above description, a magnetic noise reducing device according to the invention that comprises SQUID flux meters and noise canceling coils can produce a given space defined by the noise canceling coils that has a remarkable magnetic noise reducing effect particularly against magnetic noise of low frequency range.

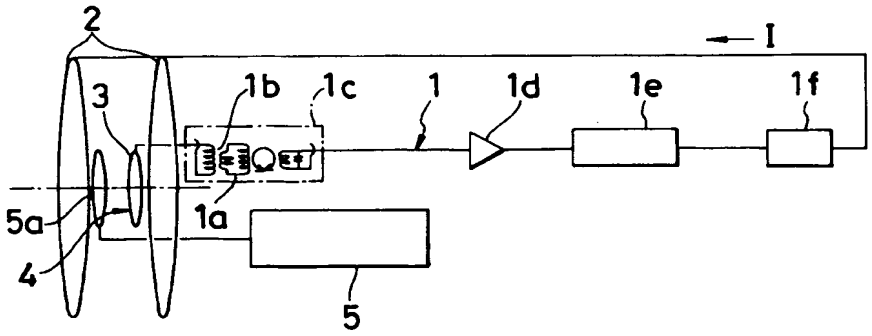
Besides, since a magnetic noise reducing device according to the invention can cancel net environmental magnetic noise within the magnetic space where the magnetic flux detecting coils are located, it is particularly useful for simultaneous multiple-point measurement of biomagnetism.

Since a magnetic noise reducing device according to the invention can comprise any appropriate number of SQUID flux meters and noise canceling coils for effectively reducing magnetic noise, it provide an effective method of magnetic noise reduction that does not involve the use of a costly magnetism shield room or a gradiometer of higher order that can be realized at the cost of sensitivity of the SQUID flux meter it comprises.

Claims

1. A magnetic noise reducing device comprising an appropriate number of noise cancelling coils and corresponding matching SQUID flux meters each having a magnetic flux detecting coil arranged within a specific space defined by the corresponding noise cancelling coils, the output of each of said SQUID flux meter being supplied to said corresponding noise cancelling coils as a feedback current.

FIG.1(A)


2
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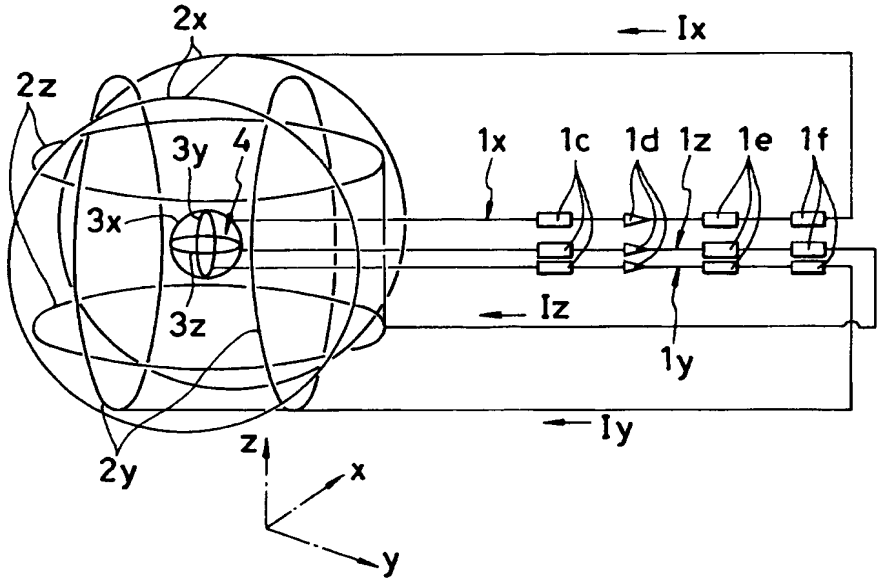
1b
1c
1
1d
1e
1f
5a
1a
4
5

FIG.1(B)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Ix
2z
1x
1c
1d
1z
1e
1f
3y
4
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3z
Iz
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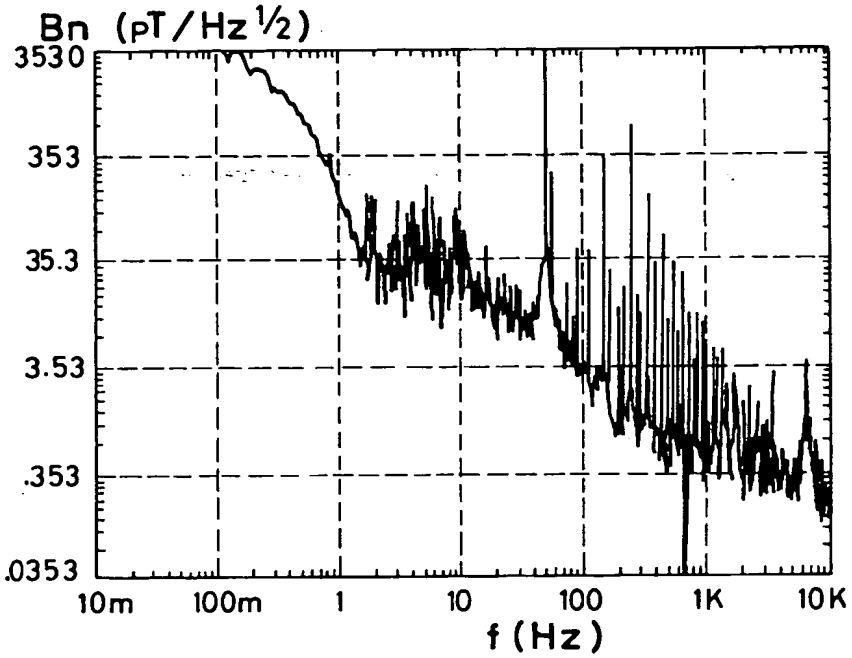
y

FIG.2(A)


Bn (pT/Hz 1/2)
3530
353
35.3
3.53
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.0353
10m
100m
1
10
100
1K
10K
f (Hz)

FIG.2(B)

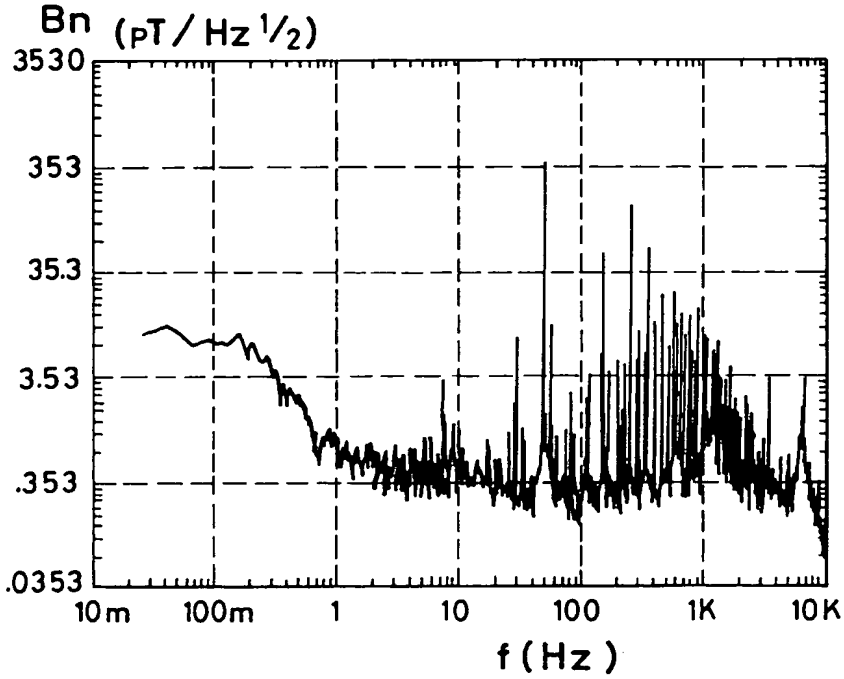

Bn (pT/Hz 1/2)
3530
353
35.3
3.53
.353
.0353
10m
100m
1
10
100
1K
10K
f (Hz)

FIG. 3

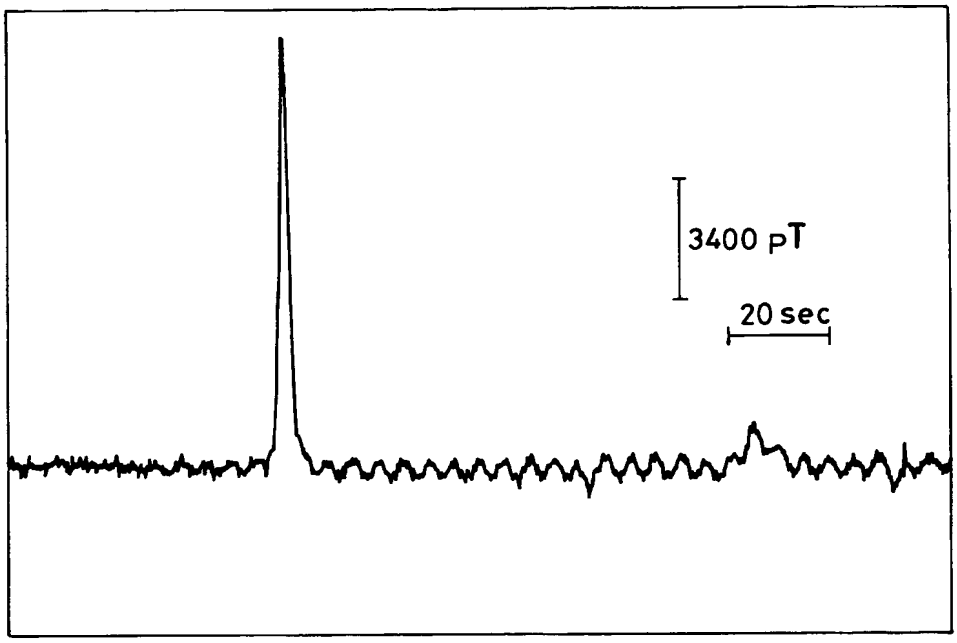


FIG. 4

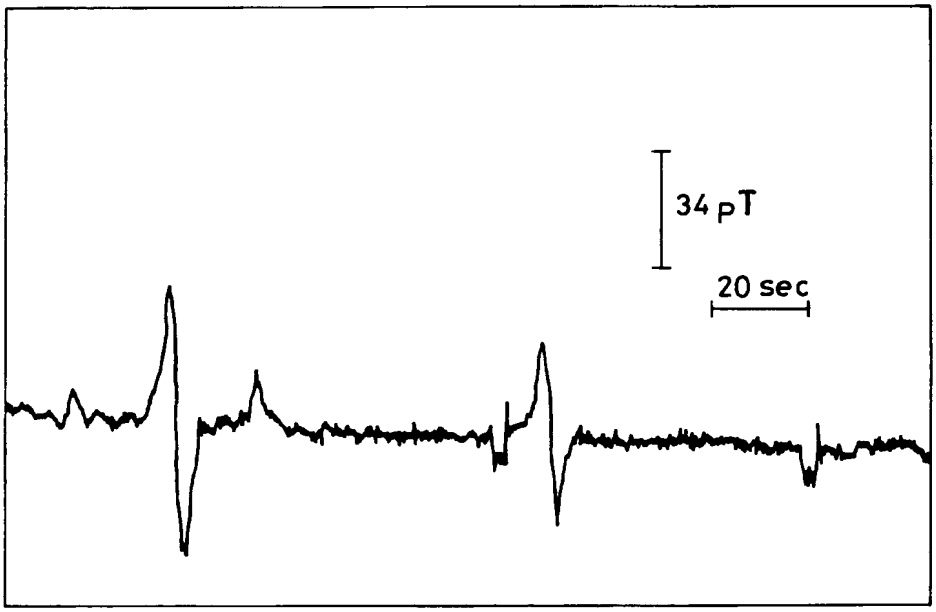
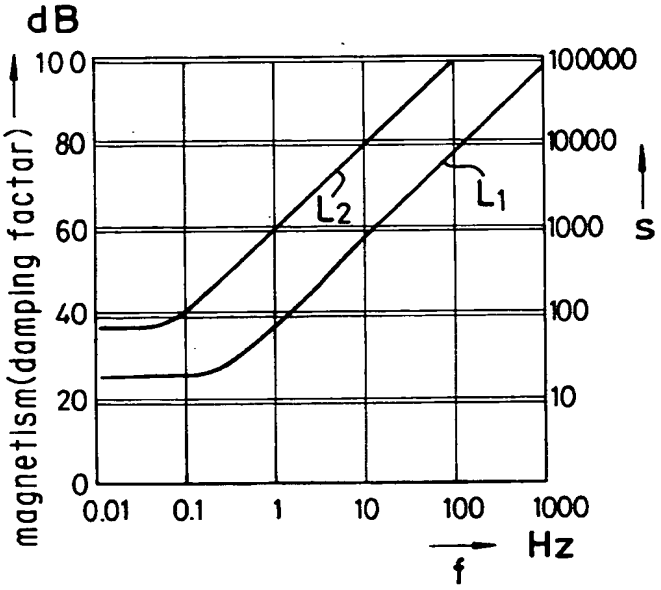


FIG.5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100
80
60
40
20
0
magnetism(dampIng factar)
100000
10000
1000
100
10
S
L2
L1
0.01
0.1
1
10
100
1000
Hz
f

FIG.6

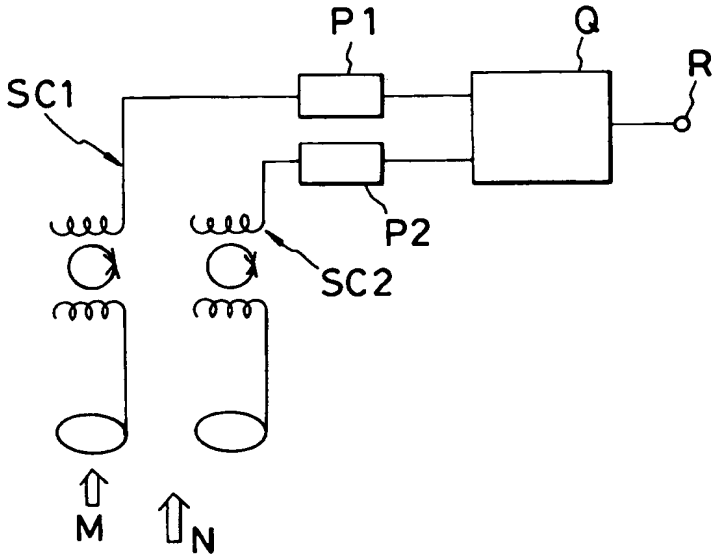
P1
Q
R
SC1
P2
SC2
M
N

FIG.7

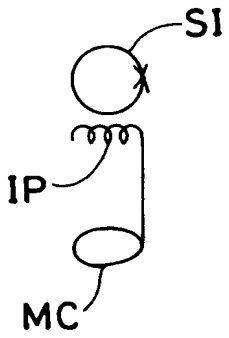
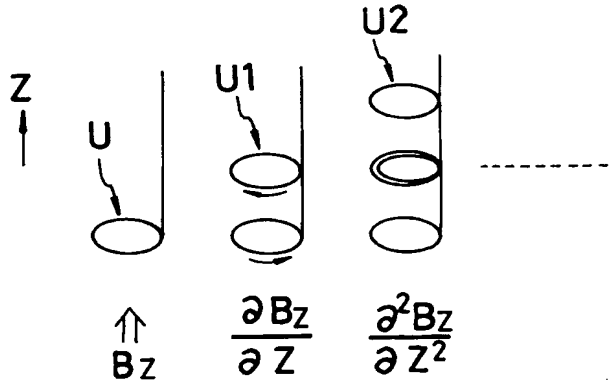
FIG.8